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APPROXIMATE METHOD FOR DETERMINING EQUILIBRIUM OPERATION OF COMPRESSOR COMPONENT OF TURBOJET ENGINE

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SUMMARY

A method is presented for estimating the equilibrium operating line for a compressor as a component part of a turbojet engine. The performance characteristics of the combustor, turbine, and jet nozzle are treated in a simplified manner, so that the suitability of a given compressor for jet-engine application may be determined. The need for compressor-discharge bleed, a variable-area jet nozzle, or both, to obtain satisfactory engine acceleration may be estimated from the position of the equilibrium operating line and the compressor surge line.

Charts are presented that may be used to locate the equilibrium operating line on the performance map of the compressor component of a turbojet engine operating at sea-level static conditions.

A comparison of predicted and measured equilibrium operating conditions in terms of compressor pressure ratio and equivalent weight flow indicates satisfactory agreement.

INTRODUCTION

In general, an accurate prediction of the equilibrium operating conditions of a turbojet engine requires a knowledge of the performance characteristics of each of the component parts of the engine. An analysis of the performance of a turbojet engine based on the performance characteristics of its component parts is presented in reference 1. Because of the many variables involved and the complexity of the component characteristics, the computations are lengthy and the results lack generality.

A method of predicting the equilibrium operating performance of turbojet engines in which the complicated component processes are treated in a simplified manner is presented in reference 2. The results are somewhat more general than those of reference 1 and demonstrate the adequacy of the model processes used. The compressor model used in the analysis was one in which the ratio of axial inlet-air velocity to compressor tip velocity was a constant. In many cases the compressor performance characteristics are known, so that the simplified model of the compressor is not required, and the principal question is whether the known compressor stall or surge line is such as to provide adequate margin for engine acceleration. Since the compressor stall or surge line is generally given as a plot of compressor pressure ratio against corrected inlet weight flow, in order to compare results it seems desirable to obtain the equilibrium performance in terms of these variables. 3653

The purpose of this report is to obtain generalized charts to permit rapid computation of equilibrium operating points on the performance map of the compressor component of a turbojet engine operating at static sea-level conditions. The effect of heat addition in an afterburner on the operating line is not considered, because engines are normally accelerated from low speeds with the afterburner inoperative (if the engine is so equipped). The method incorporates simplified performance characteristics of the turbine, jet nozzle, and burner components. The work was done at the NACA Lewis laboratory.

SYMBOLS

The following symbols are used in this report:

A effective cross-sectional area, sq ft

a speed of sound, ft/sec

B ratio of air flow bled from compressor discharge to compressor-inlet air flow

f fuel-air ratio

g acceleration due to gravity, 32.17405 ft/sec^2

P total pressure, lb/sq ft

p static pressure, lb/sq ft

R gas constant, 53.345 ft-lb/(lb)($^{\circ}$R)

T total temperature, $^{\circ}$R

U blade speed, ft/sec

V absolute velocity, ft/sec

w weight flow of air, lb/sec

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CK-1 back

α absolute gas flow angle measured from axial direction, deg

γ ratio of specific heat at constant pressure to specific heat at constant volume

δ ratio of compressor-inlet total pressure to NACA standard sea-level absolute pressure, P/2116

η adiabatic efficiency

η_p polytropic efficiency

θ ratio of compressor-inlet total temperature to NACA standard sea-level absolute temperature, $T/518.7^{\circ}$

$\varkappa$ tail-pipe total-pressure-loss coefficient

ρ density, lb/cu ft

ψ pressure coefficient

Subscripts:

C compressor

T turbine

0 ambient conditions

1 compressor inlet

2 compressor outlet and combustor inlet

3 turbine-nozzle discharge

4 turbine outlet and tail-pipe inlet

5 jet-nozzle outlet

Superscript:

* value at choked-flow conditions

Parameters:

$$\overline{A} = \frac{A_5}{A_3}\left(\frac{w^*}{w}\right)_3 \frac{w_3}{w_5}$$

$$\overline{P} = \frac{P_2}{P_1}\frac{P_3}{P_2}\frac{P_1}{p_0}\frac{p_0}{p_5}$$

$$\overline{T} = (1 - B + f)\,\frac{T_3}{T_1}\,\eta_C\eta_T$$

$$\overline{w} = \sqrt{\frac{1 - B + f}{\eta_C\eta_T}}\,\frac{w_5}{w_3}\,\frac{A_1}{A_5}\,\frac{w_1\sqrt{\theta}}{\delta A_1}$$

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ANALYSIS

Equilibrium operation of the components of a jet engine requires that the turbine power output be equal to the power required to drive the compressor plus bearing losses and power that may be extracted from the turbine to drive engine accessories. At sea-level static conditions the bearing losses and accessory power are generally negligible compared with the power required to drive the compressor and consequently will be neglected in the following analysis. This power-equality requirement may be stated in equation form as follows:

$$(1 - B + f)\,\frac{T_3}{T_1}\,\eta_C\eta_T = \frac{\gamma_1}{\gamma_1 - 1}\,\frac{\gamma_3 - 1}{\gamma_3}\,\frac{\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1\right]}{\left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma_3 - 1}{\gamma_3}}\right]} = \overline{T} \qquad (1)$$

The station numbering system used is shown in figure 1. In order to determine the turbine-inlet temperature T_3 required to drive the compressor, a relation between the pressure ratio of the compressor P_2/P_1 and the pressure ratio of the turbine P_3/P_4 must be known. Such a relation may be obtained by making use of simplified models for the turbine and jet nozzle similar to those used in reference 2.

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Turbine and Jet Nozzle

The ratio of the turbine-inlet total pressure to the ambient static pressure at the jet-nozzle throat is related to the turbine total-pressure ratio as follows in terms of pressure ratios of interest:

$$\frac{P_3}{p_5} = \frac{P_3}{P_4}\frac{P_4}{P_5}\frac{P_5}{p_5} \tag{2}$$

In order to estimate the ratio P_4/P_5, the loss in total pressure between station 4 and the jet nozzle at station 5 is assumed to vary with the velocity at station 5 in the following way:

$$P_4 - P_5 = \varkappa \frac{\rho_5 V_5^2}{2g} \tag{3}$$

In terms of the ratio of total to static pressure at station 5, expression (3) becomes the following:

$$\frac{P_4}{P_5} = 1 + \frac{\gamma_5}{\gamma_5-1}\varkappa\frac{p_5}{P_5}\left[\left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5-1}{\gamma_5}} - 1\right] \tag{4}$$

If expression (4) is combined with expression (2), the following is obtained:

$$\frac{P_3}{p_5} = \frac{P_3}{P_4}\left\{1 + \frac{\gamma_5\varkappa}{\gamma_5-1}\frac{p_5}{P_5}\left[\left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5-1}{\gamma_5}} - 1\right]\right\}\frac{P_5}{p_5} \tag{5}$$

The jet nozzle becomes choked when

$$\frac{P_5}{p_5} = \left(\frac{\gamma_5+1}{2}\right)^{\frac{\gamma_5}{\gamma_5-1}} \tag{6}$$

Since a simple converging nozzle is considered, P_5/p_5 cannot exceed the value of choked flow as given by expression (6). In order to relate the turbine pressure ratio to the area of the jet nozzle, other relations in addition to equation (5) are required. These required relations may be obtained from continuity considerations.

From continuity considerations the following is obtained:

$$\frac{w_3\sqrt{T_3}}{P_3A_3} = \frac{w_5\sqrt{T_5}}{P_5A_5}\,\frac{P_5}{P_4}\,\frac{P_4}{P_3}\sqrt{\frac{T_3}{T_5}}\,\frac{A_5}{A_3}\,\frac{w_3}{w_5} \tag{7}$$

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In most cases the ratio w_3/w_5 is equal to 1, but the term is retained so that cases where cooling air is added or hot gases are bled from the tail pipe may be considered. For one-dimensional compressible flow through the jet nozzle, the following applies:

$$\frac{w_5\sqrt{T_5}}{P_5A_5} = \sqrt{\frac{2\gamma_5}{\gamma_5-1}\,\frac{g}{R}}\sqrt{\left(\frac{p_5}{P_5}\right)^{\frac{2}{\gamma_5}} - \left(\frac{p_5}{P_5}\right)^{\frac{\gamma_5+1}{\gamma_5}}} \tag{8}$$

When the effective area A_5 is choked, P_5/p_5 is the value given by equation (6), and expression (8) becomes

$$\frac{w_5^*\sqrt{T_5}}{P_5A_5} = \sqrt{\frac{\gamma_5 g}{R}\left(\frac{2}{\gamma_5+1}\right)^{\frac{\gamma_5+1}{\gamma_5-1}}} \tag{9}$$

Similarly,

$$\left(\frac{w}{w^*}\right)_3 = \frac{w_3\sqrt{T_3}}{P_3A_3}\sqrt{\frac{R}{g\gamma_3}\left(\frac{\gamma_3+1}{2}\right)^{\frac{\gamma_3+1}{\gamma_3-1}}} \tag{10}$$

The temperature ratio T_3/T_4 is related to the turbine pressure ratio P_3/P_4 and the turbine polytropic efficiency as follows:

$$\frac{T_3}{T_4} = \frac{P_3}{P_4}^{\frac{(\gamma_3-1)}{\gamma_3}\eta_{p,T}} \tag{11}$$

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For negligible heat loss between stations 4 and 5, $T_4 = T_5$. The pressure ratio P_4/P_5 is given by expression (4). If expressions (4), (8), (10), and (11) are substituted into expression (7), the following is obtained:

$$\frac{\left[\sqrt{\left(\frac{P_5}{p_5}\right)^{\frac{2}{\gamma_5}} - \left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5+1}{\gamma_5}}}\right]\bar{A}}{\sqrt{\left(\frac{\gamma_5-1}{2}\right)\frac{\gamma_3}{\gamma_5}\left(\frac{2}{\gamma_3+1}\right)^{\frac{\gamma_3+1}{\gamma_3-1}}\left\{1+\varkappa\frac{\gamma_5}{\gamma_5-1}\frac{p_5}{P_5}\left[\left(\frac{P_5}{p_5}\right)^{\frac{\gamma_5-1}{\gamma_5}}-1\right]\right\}}} = \left(\frac{P_3}{P_4}\right)^{\left(1-\frac{\gamma_3-1}{2\gamma_3}\eta_{p,T}\right)} \tag{12}$$

where

$$\bar{A} = \frac{A_5}{A_3}\left(\frac{w^*}{w}\right)_3 \frac{w_3}{w_5}$$

Expression (12) relates the turbine pressure ratio P_3/P_4 to the parameter $\bar{A}$ in terms of the ratio of total to static pressure in the jet nozzle P_5/p_5 and the loss coefficient $\varkappa$. The turbine pressure ratio reaches a maximum for any value of $\bar{A}$ when the jet nozzle chokes.

Compressor Pressure Ratio

The compressor pressure ratio is related to the pressure ratio across the turbine and jet nozzle P_3/p_5 in the following way:

$$\frac{P_3}{p_5} = \frac{P_2}{P_1}\frac{P_3}{P_2}\frac{P_1}{p_0}\frac{p_0}{p_5} = \bar{P} \tag{13}$$

The combustor pressure ratio P_3/P_2 in general depends on the combustor-inlet velocity pressure and the ratio of combustor-outlet to -inlet temperature T_3/T_2 (e.g., ref. 3). In the following analysis the burner pressure ratio is considered a constant, as in reference 2.

The ratio P_1/p_0 is the ram pressure ratio, which depends on the flight Mach number and ram recovery of the engine inlet. For a simple convergent jet nozzle operating with exit Mach numbers less than 1, that is, for values of P_5/p_5 less than that given by expression (6), $p_5 = p_0$. Inasmuch as the turbine pressure ratio P_3/P_4 reaches a maximum when the jet nozzle is choked (see expression (12)), the parameter $\overline{P}$ also reaches a maximum when the jet nozzle chokes (see expressions (5) and (13)). Consequently, for given values of combustor pressure ratio P_3/P_2 and ram pressure ratio P_1/p_0, the product $(P_2/P_1)(p_0/p_5)$ is a constant when the jet nozzle is choked.

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The desired relation between compressor pressure ratio and turbine pressure ratio needed for use with expression (1) is given by expressions (5), (12), and (13). Figure 2 was constructed by use of expressions (5), (12), and (13) for $\gamma_3 = \gamma_5 = 4/3$, $\eta_{p,T} = 0.85$, and $\varkappa = 0.14$. With this value of $\varkappa$, $P_4/P_5 = 1.05$ for sonic velocity in the jet nozzle. The turbine pressure ratio P_3/P_4 is plotted against the parameter $\overline{P}$ for various values of the parameter $\overline{A}$. The lines of constant values of P_5/p_5 are also included for reference.

Equilibrium Operation

The turbine pressure ratio may be determined for any given value of compressor pressure ratio, ram pressure ratio, and combustor pressure ratio in terms of the parameter $\overline{A}$ by use of figure 2. With the turbine pressure ratio known for each compressor pressure ratio, equation (1) may be solved for the parameter $\overline{T}$. The turbine-inlet temperature T_3 required for equilibrium operation is thus determined in terms of the compressor and turbine efficiency, the percentage of the compressor-inlet air flow bled from the compressor discharge B, and the combustor fuel-air ratio f. The variation of the parameter $\overline{T}$ with compressor pressure ratio P_2/P_1 for various values of the parameter $\overline{A}$ is shown in figure 3. The ram pressure ratio P_1/p_0 was taken equal to 1 (static conditions), and the combustor pressure ratio P_3/P_2 was taken equal to 0.97. The jet-nozzle choking line and lines for turbine pressure ratios P_3/P_4 of 2 and 2.5 are included for reference. As can be seen from the figure, the parameter $\overline{T}$ varies nearly linearly with compressor pressure ratio over a range of compressor pressure ratios for all values of the parameter $\overline{A}$. For cases where $(w^*/w)_3 = 1$ (choked turbine nozzle), $w_3 = w_5$, and $B = f$ (leakage and cooling-air flow at compressor discharge equal to fuel flow), figure 3 represents the variation of $(T_3/T_1)(\eta_C\eta_T)$ at equilibrium with compressor pressure ratio for various values of the ratio of the effective areas of the jet nozzle and turbine nozzle A_5/A_3.

Compressor Weight Flow

The corrected weight flow at the compressor inlet may be determined from continuity considerations. In terms of the parameters $\bar{A}$ and $\bar{T}$, the continuity relation may be written as follows:

$$\sqrt{\frac{1 - B + f}{\eta_C \eta_T}}\,\frac{w_5}{w_3}\,\frac{A_1}{A_5}\,\frac{w_1\sqrt{\theta}}{\delta A_1} = \frac{\sqrt{\frac{g\gamma_3}{R}\left(\frac{2}{\gamma_3+1}\right)^{\frac{\gamma_3+1}{\gamma_3-1}}}\;\frac{P_2}{P_1}\,\frac{P_3}{P_2}\,\frac{2116}{\sqrt{518.7}}}{\bar{A}\sqrt{\bar{T}}} = \bar{w} \tag{14}$$

For each value of compressor pressure ratio P_2/P_1 and the parameter $\bar{A}$, the value of $\bar{T}$ for equilibrium is given by figure 3. The variation of the parameter $\bar{w}$ with compressor pressure ratio for each of several values of the parameter $\bar{A}$ is shown in figure 4. As was the case with figure 3, the burner pressure ratio P_3/P_2 was taken equal to 0.97 and γ_3 was taken equal to $4/3$. Contours of constant values of the term $\bar{T}$ are also shown along with the jet-nozzle choking line and two values of turbine pressure ratio. Compressor pressure ratio is the ordinate of figure 4, and the abscissa involves the equivalent weight flow through the compressor $w_1\sqrt{\theta}/\delta$. Compressor performance maps are generally plotted in a similar manner, with constant values of equivalent compressor speed as a parameter. The equilibrium operating line on a compressor map is the locus of equilibrium values of pressure ratio and equivalent weight flow at each compressor speed.

The use of figure 4 to estimate the equilibrium operating line involves the estimation of the variation in $(w/w^*)_3$ with compressor pressure ratio. In the range of compressor pressure ratio where the turbine nozzle is choked, that is, $(w/w^*)_3 = 1$, the estimated equilibrium operating line is the line of a constant value of the parameter $\bar{A}$ that passes through the point of design compressor pressure ratio and the design value of the parameter $\bar{T}$. At compressor pressure ratios where the turbine nozzle is not choked, the variation in $(w/w^*)_3$ may be estimated by the method outlined in the following section.

Turbine Choking

The ratio of effective areas A_5/A_3 in the parameter $\bar{A}$ remains essentially constant as the compressor pressure ratio is varied, but the ratio of the turbine weight flow w_3 to the choking value w_3^* may vary somewhat as the compressor pressure ratio is varied. The ratio $(w/w^*)_3$ is generally essentially constant over a range of compressor pressure ratios near the design value but falls to zero as the compressor pressure ratio approaches 1. The actual variation in the term $(w/w^*)_3$ with compressor pressure ratio depends somewhat on the turbine design details and the number of turbine stages used.

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In order to more definitely establish the compressor equilibrium operating line at pressure ratios somewhat less than design, the variation in $(w/w^*)_3$ with turbine pressure ratio P_3/P_4 for the two extremes of a single-stage turbine and a multistage turbine will be considered. For single-stage turbines with axial discharge from the turbine, the ratio $(w/w^*)_3$ may be estimated as follows. From continuity, the following is obtained:

$$\left(\frac{w}{w^*}\right)_3 = \left(\frac{\gamma_3+1}{2}\right)^{\frac{1}{\gamma_3-1}} \left[1 - \frac{\gamma_3-1}{\gamma_3+1}\left(\frac{V}{a^*}\right)_3^2\right]^{\frac{1}{\gamma_3-1}} \left(\frac{V}{a^*}\right)_3 \tag{15}$$

Let

$$\psi_T = \frac{V_3 \sin \alpha_3}{U_T} \tag{16}$$

$$\frac{T_3 - T_4}{T_3} = \eta_T \left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma_3-1}{\gamma_3}}\right] \tag{17}$$

and, from $T_3 - T_4 = \frac{\gamma_3-1}{\gamma_3 Rg} U_T V_3 \sin \alpha_3$,

$$\frac{T_3 - T_4}{T_3} = 2\frac{\gamma_3-1}{\gamma_3+1} \psi_T \left(\frac{U_T}{a^*}\right)^2 \tag{18}$$

Substitution of expressions (16) to (18) into (15) yields the following:

$$\left(\frac{w}{w^*}\right)_3 = \left(\frac{\gamma_3+1}{2}\right)^{\frac{1}{\gamma_3-1}} \sqrt{\frac{\gamma_3+1}{2(\gamma_3-1)}} \left\{1 - \frac{\psi_T\eta_T}{2\sin^2\alpha_3}\left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma_3-1}{\gamma_3}}\right]\right\}^{\frac{1}{\gamma_3-1}} \left\{\frac{\psi_T\eta_T}{\sin^2\alpha_3}\left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{\gamma_3-1}{\gamma_3}}\right]\right\}^{\frac{1}{2}} \tag{19}$$

For single-stage turbines, the pressure coefficient ψ_T is generally no greater than 2 and the turbine-nozzle discharge flow angle α_3 is generally between 60° and 70°. The value of ψ_T is approximately constant along the equilibrium operating line.

For multistage turbines, the ratio of the weight flow to critical weight flow may be approximated by the following formula taken from reference 4:

$$\left(\frac{w}{w^*}\right)_3 = \sqrt{1 - \left(\frac{P_4}{P_3}\right)^2} \tag{20}$$

The ratio of the weight flow to critical weight flow $(w/w^*)_3$ determined by expression (19) for values of the parameter $\psi_T\eta_T/\sin^2\alpha_3$ of 1.5 and 2 is plotted in figure 5 along with values determined by expression (20). As can be seen from the figure, $(w/w^*)_3$ is substantially constant for turbine pressure ratios greater than about 2.5 for the multistage turbine and about 2 for the single-stage turbine. Operating lines for two- or three-stage turbines would presumably fall between those for the single-stage and that for the multistage turbine.

DISCUSSION

The charts included in the report (figs. 2 to 4) for use in estimating the equilibrium operating line were constructed on the basis of the following assumptions with regard to pressure losses in the combustor and tail pipe:

(1) Combustor pressure ratio $P_3/P_2 = 0.97$

(2) Tail-pipe loss coefficient $\varkappa = 0.14$, resulting in tail-pipe pressure ratio $P_4/P_5 = 1.05$ when jet nozzle is choked

These assumed losses are consistent with modern jet-engine component characteristics.

The ram pressure ratio used in constructing figures 3 and 4 corresponds to static conditions with no engine-inlet losses. For conditions when the jet nozzle is choked, the values of the parameters $\overline{T}$, $\overline{A}$, and $\overline{w}$ in figures 3 and 4 would be the same for all values of ram pressure ratio greater than 1. That is, for a given value of compressor pressure ratio P_2/P_1 and parameter $\overline{A}$ such that the jet nozzle is choked, the values of $\overline{T}$ and $\overline{w}$ given in figures 3 and 4 would be the same for all values of ram pressure ratio greater than 1. If, however, the jet nozzle is not choked, an increase in ram pressure ratio would increase $\overline{P}$ and consequently increase the turbine pressure ratio P_3/P_4 (see fig. 2). The increased turbine pressure ratio would result in a value of the parameter $\overline{T}$ less than that given by figure 3 and consequently a value of the parameter $\overline{w}$ greater than that given by figure 4. Therefore, increased ram pressure ratio tends to shift the equilibrium operating line to higher values of compressor weight flow $w_1\sqrt{\theta}/\delta$ when the jet nozzle is not choked, but has no effect on the operating line when the jet nozzle is choked.

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Design-Point Operation

The equilibrium operating line based on the assumptions used may be estimated by use of figures 2 to 5 as follows. At design conditions the compressor pressure ratio P_2/P_1, weight flow $w\sqrt{\theta}/\delta A_1$, and the ratio of turbine-inlet to compressor-inlet temperature T_3/T_1 are specified. If the compressor performance map is known, the compressor efficiency η_C is determined. An attainable value of turbine efficiency based on past experience may be estimated along with the value of bleed B, which accounts for air bled for cooling or other purposes and seal leakage. The value of w_3/w_5 is also given by the design and will generally be equal to 1 unless some form of turbine cooling is incorporated in the design. [In cases where air-cooling of the turbine is used, air may be bled from the compressor, passed through hollow turbine blades, and discharged into the tail pipe. In cases where the value of B consists of only seal-leakage flow, it may be sufficiently accurate to consider the fuel flow equal to the leakage flow (B = f). If, however, additional refinement is desired, the fuel-air ratio f may be calculated from values of T_2 and T_3 for an assumed combustion efficiency by use of charts such as those presented in ref. 5.] The design conditions then determine $\overline{T}$ and P_2/P_1, and the value of $\overline{A}$ may be read from figure 3 or figure 4. The corresponding value of $\overline{w}$ is read from figure 4. The only unknown in $\overline{w}$ at design conditions is the jet-nozzle area term A_5/A_1, which may be computed if desired. Design conditions thus determine the value of $\overline{A}$ and the jet-nozzle area-ratio parameter A_5/A_1.

Off-Design Operation

For a fixed-geometry engine - that is, where A_3/A_5 and A_5/A_1 are kept constant as the compressor pressure ratio is varied - the operating line is the line of constant $\overline{A}$ ($\overline{A}$ determined by the design conditions) over the range of compressor pressure ratios for which $(w/w^*)_3$ is constant. As shown by figure 5, $(w/w^*)_3$ is nearly constant for turbine pressure ratios greater than about 2.5 for a multistage turbine or greater than about 2 for a single-stage turbine. The lines indicating turbine pressure ratios of 2.0 and 2.5 were added to figures 3 and 4 to aid in determining for any value of $\overline{A}$ the range of compressor pressure ratios over which the turbine nozzle is essentially choked. In many cases the turbine nozzle will be essentially choked over the entire range of compressor pressure ratios of interest. If, however, it is desired to determine operating points in a range of compressor pressure ratios where the turbine nozzle is not choked, the variation in the value of $\overline{A}$ from its value at the design point may be estimated by use of figures 2 and 5. Figure 2 is used to determine the turbine pressure ratio for the design value of $\overline{A}$, and figure 5 is used to estimate the value of $(w/w^*)_3$.

The effective area ratio A_5/A_3, which remains essentially constant for all engine operation, is calculated from the design values of $\overline{A}$ and $(w/w^*)_3$. For a selected compressor pressure ratio P_2/P_1, a trial value of $(w/w^*)_3$ is selected and a trial value of $\overline{A}$ is calculated. From the selected compressor pressure ratio and the trial value of $\overline{A}$, a turbine pressure ratio P_3/P_4 is read from figure 2 that allows a value of $(w/w^*)_3$ to be read from figure 5. If this is not equal to the trial value of $(w/w^*)_3$, the process is repeated until the two values agree. The final value of the parameter $\overline{A}$ is then used in figure 4 to obtain the value of $\overline{w}$.

A trial value of compressor weight flow $w\sqrt{\theta}/\delta$ may be computed from $\overline{w}$ and estimated values of η_C and η_T. The value of η_C obtained from the compressor map corresponding to the selected pressure ratio and computed $w\sqrt{\theta}/\delta$ is then compared with the estimated value of η_C. When the estimated efficiency and the value on the compressor map at the estimated operation point agree, the operating point is located on the compressor map. The most conservative (lowest) values of the parameter $\overline{w}$ and $w\sqrt{\theta}/\delta$ will naturally be obtained if the multistage turbine is considered. If, however, the jet engine considered has a compressor pressure ratio P_2/P_1 less than about 5, a single-stage turbine may be adequate.

A comparison of the estimated equilibrium operating line with the compressor stall-limit line may be used to determine the necessity for the use of variable-geometry devices to aid in obtaining satisfactory engine acceleration. The effect of compressor-discharge bleed and a variable-area jet nozzle can be obtained directly from the charts.

Effect of Compressor-Discharge Bleed

The effect of compressor-discharge bleed on the equilibrium operating line may be estimated by use of figure 4. The principal effect of bleed will be to change the value of $(T_3/T_1)\eta_C\eta_T$ in the parameter $\overline{T}$ and $w_1\sqrt{\theta}/\delta$ in the parameter $\overline{w}$. In general, at a given compressor pressure ratio an increase in bleed results in an increase in the value of T_3/T_1 and $w\sqrt{\theta}/\delta$. The operating line is moved away from the stall line, but the turbine-inlet temperature is increased.

Effect of Jet-Nozzle Adjustment

The effects of adjusting the jet-nozzle area may be estimated by considering the effect of the variation of A_5/A_3 in the parameter $\overline{A}$ and of A_5/A_1 in the parameter $\overline{w}$. Inasmuch as a change in $\overline{A}$ will cause a change in the turbine pressure ratio P_3/P_4 for a given compressor pressure ratio P_2/P_1, the variation in $(w/w^*)_3$ with compressor pressure ratio should probably be reestimated for each jet-nozzle area A_5 considered. In general, an increase in jet-nozzle area will reduce T_3/T_1 and increase $w\sqrt{\theta}/\delta$.

EXAMPLE AND COMPARISON WITH JET-ENGINE DATA

In order to illustrate the use of the method of estimating equilibrium operating performance, an example is included. The design pressure ratio of the compressor is 6.6, and the design value of $(T_3/T_1)\eta_C\eta_T$ is 2.8. The amount of air bled from the compressor discharge is estimated to be equal to the fuel flow, that is, $B = f$. No cooling air is discharged into the tail pipe, so $w_3 = w_5$. The corresponding value of $\bar{A}$ from figure 4 is 2.585. The equilibrium operating line for a choked turbine is the line on figure 4 for the value of $\bar{A} = 2.585$. The deviation from the operating line with a choked turbine is obtained by determining the variation in turbine pressure ratio P_3/P_4 with compressor pressure ratio P_2/P_1 from figure 2, for a value of $\bar{A} = 2.585$. The variation in $(w/w^*)_3$ is then estimated by use of figure 5. The estimated equilibrium operating lines for a choked turbine, a single-stage turbine with a value of $\psi_T\eta_T/\sin^2\alpha_3 = 1.5$, and for a multistage turbine are shown in figure 6. Data obtained from a jet engine incorporating the compressor considered driven by a two-stage turbine and using a simple conical jet nozzle are shown in figure 6 for comparison. The jet-engine data were obtained at sea-level static conditions (i.e., $P_1/p_0 = 1$). The ordinate and abscissa of figure 6 have been divided by the corresponding design values. The data points lie between the predicted operating lines for the single-stage turbine and the multistage turbine. The agreement between the predicted and measured operating lines is considered satisfactory.

CONCLUDING REMARKS

A method has been presented for estimating the equilibrium operating line for a compressor as a component part of a turbojet engine. The performance characteristics of the combustor, turbine, and jet nozzle have been treated in a simplified manner, so that the suitability of a given compressor for jet-engine application may be determined. The need for variable-geometry devices to obtain satisfactory engine acceleration may be determined from the position of the equilibrium operating line relative to the compressor stall-limit (surge) line. The effects of compressor-discharge bleed and a variable-area jet nozzle can be estimated directly from the charts presented.

The results of the analysis are presented in chart form to facilitate rapid determination of equilibrium operating lines of a jet engine operated at static sea-level conditions.

A comparison of predicted and measured equilibrium operating conditions in terms of compressor pressure ratio and equivalent weight flow indicates satisfactory agreement.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 12, 1955

REFERENCES

1. Goldstein, Arthur W.: Analysis of Performance of a Jet Engine from Characteristics of Components. I - Aerodynamic and Matching Characteristics of Turbine Component Determined with Cold Air. NACA Rep. 878, 1947. (Supersedes NACA TN 1459.)

2. Sanders, John C., and Chapin, Edward C.: Equilibrium Operating Performance of Axial-Flow Turbojet Engines by Means of Idealized Analyses. NACA Rep. 987, 1950. (Supersedes NACA TN 1956.)

3. Pinkel, I. Irving, and Shames, Harold: Analysis of Jet-Propulsion-Engine Combustion-Chamber Pressure Losses. NACA Rep. 880, 1947. (Supersedes NACA TN 1180.)

4. Mallinson, D. H., and Lewis, W. G. E.: The Part-Load Performance of Various Gas-Turbine Engine Schemes. War Emergency Issue No. 41, pub. by Inst. Mech. Eng. (London). (Reprinted in U.S. by A.S.M.E., Apr. 1949, pp. 198-219.)

5. English, Robert E., and Wachtl, William W.: Charts of Thermodynamic Properties of Air and Combustion Products from 300° to 3500° R. NACA TN 2071, 1950.

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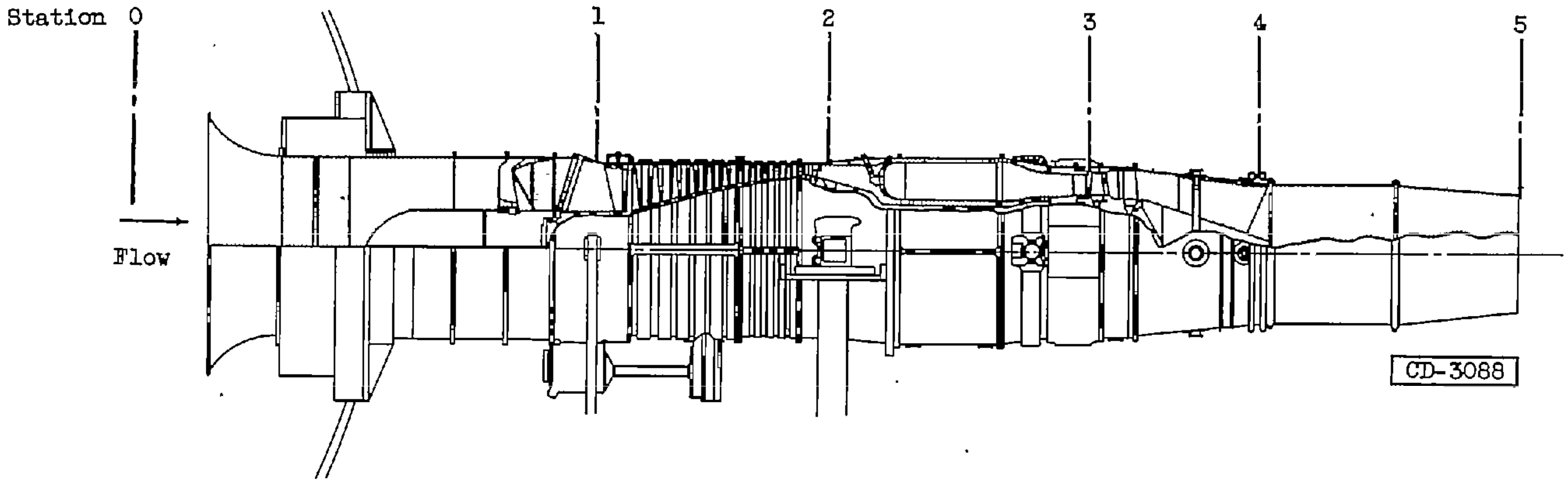

Figure 1. - Cross section of jet engine.

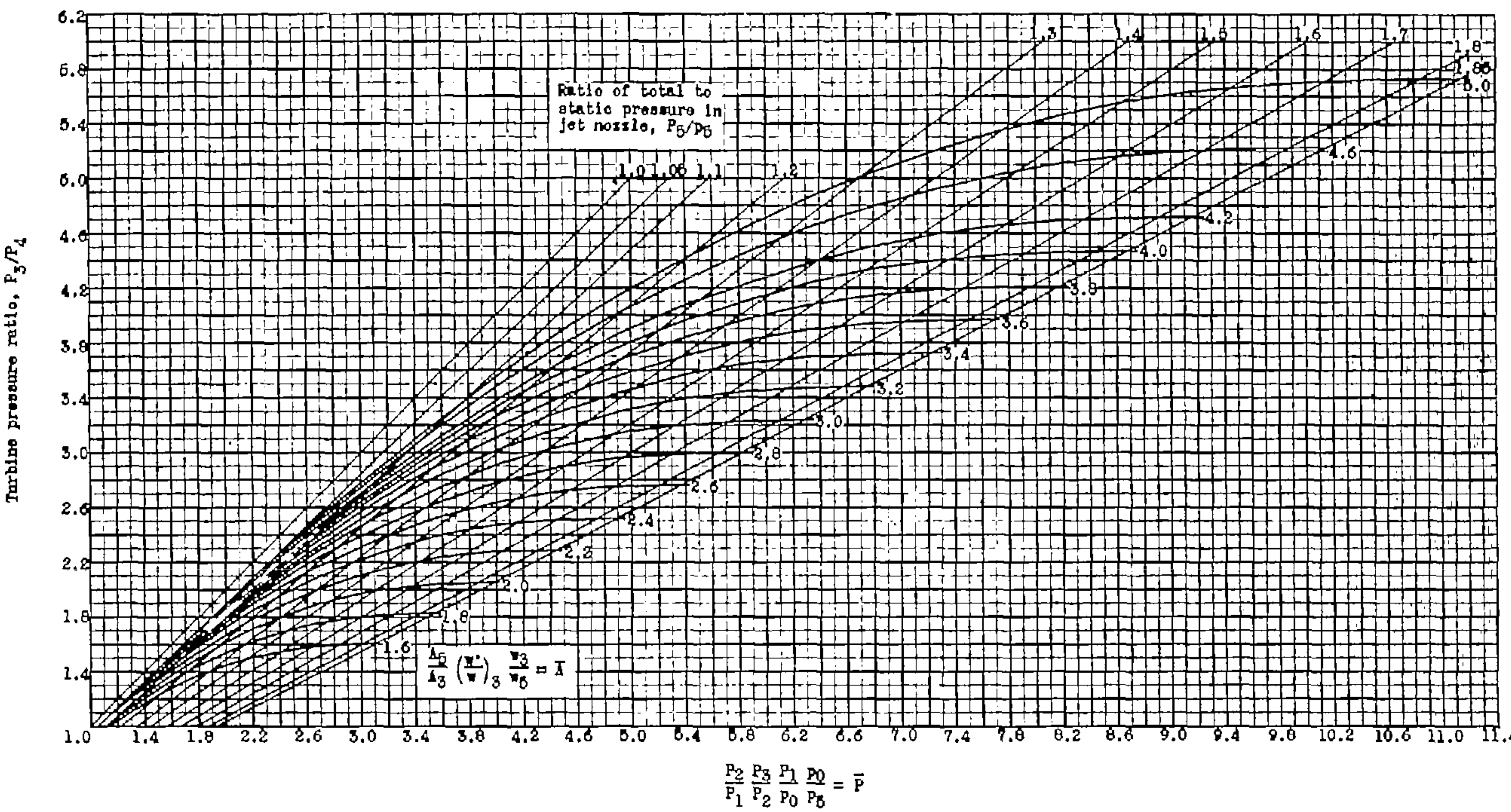

Figure 2. - Chart for estimating turbine pressure ratio.

(A large working copy of this chart may be obtained by using the request card bound in the back of the report.)

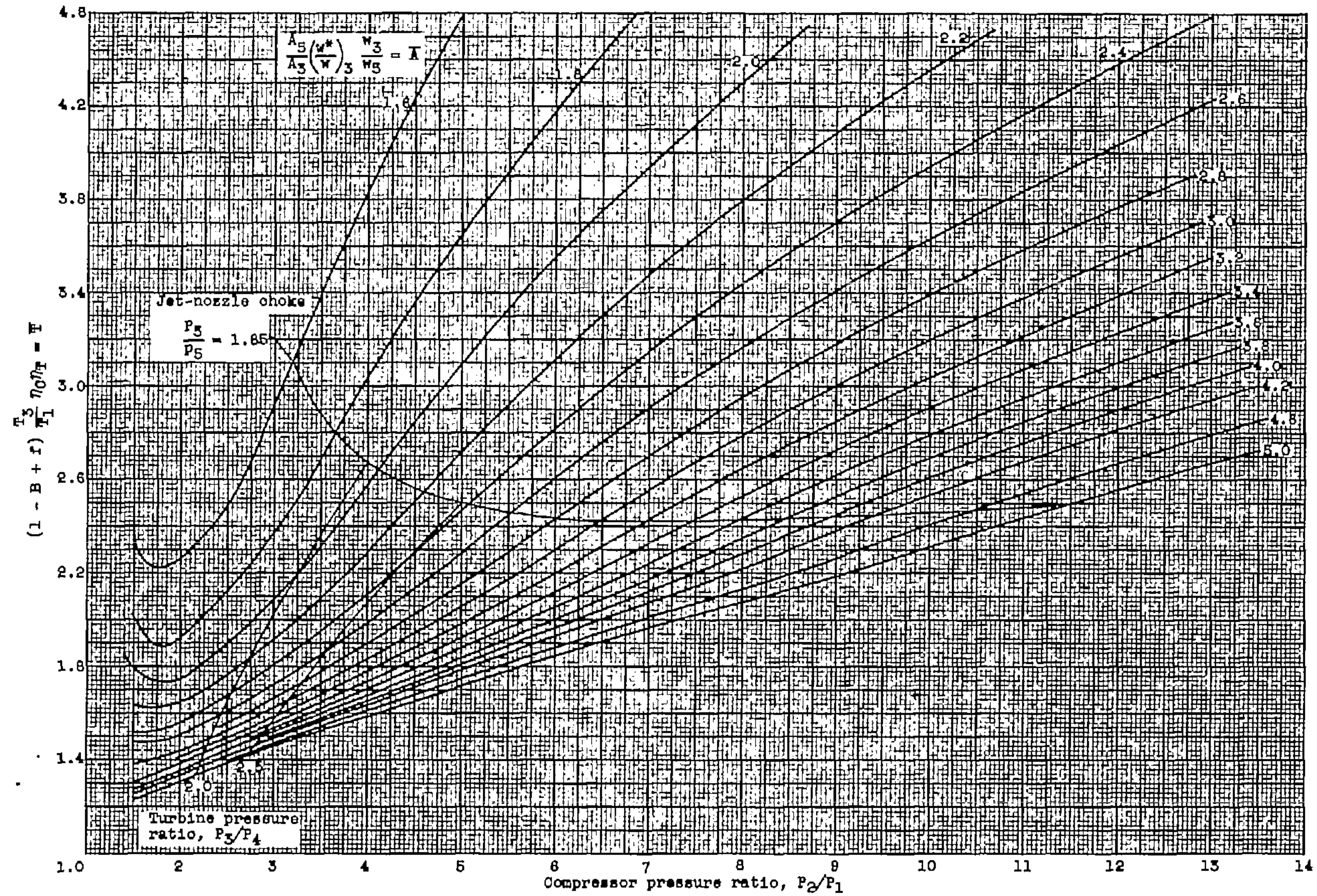

Figure 3. - Chart for estimating turbine-inlet temperature. Ram pressure ratio, P_1/p_0, 1; combustor pressure ratio, P_3/P_2, 0.97. (A large working copy of this chart may be obtained by using the request card bound in the back of the report.)

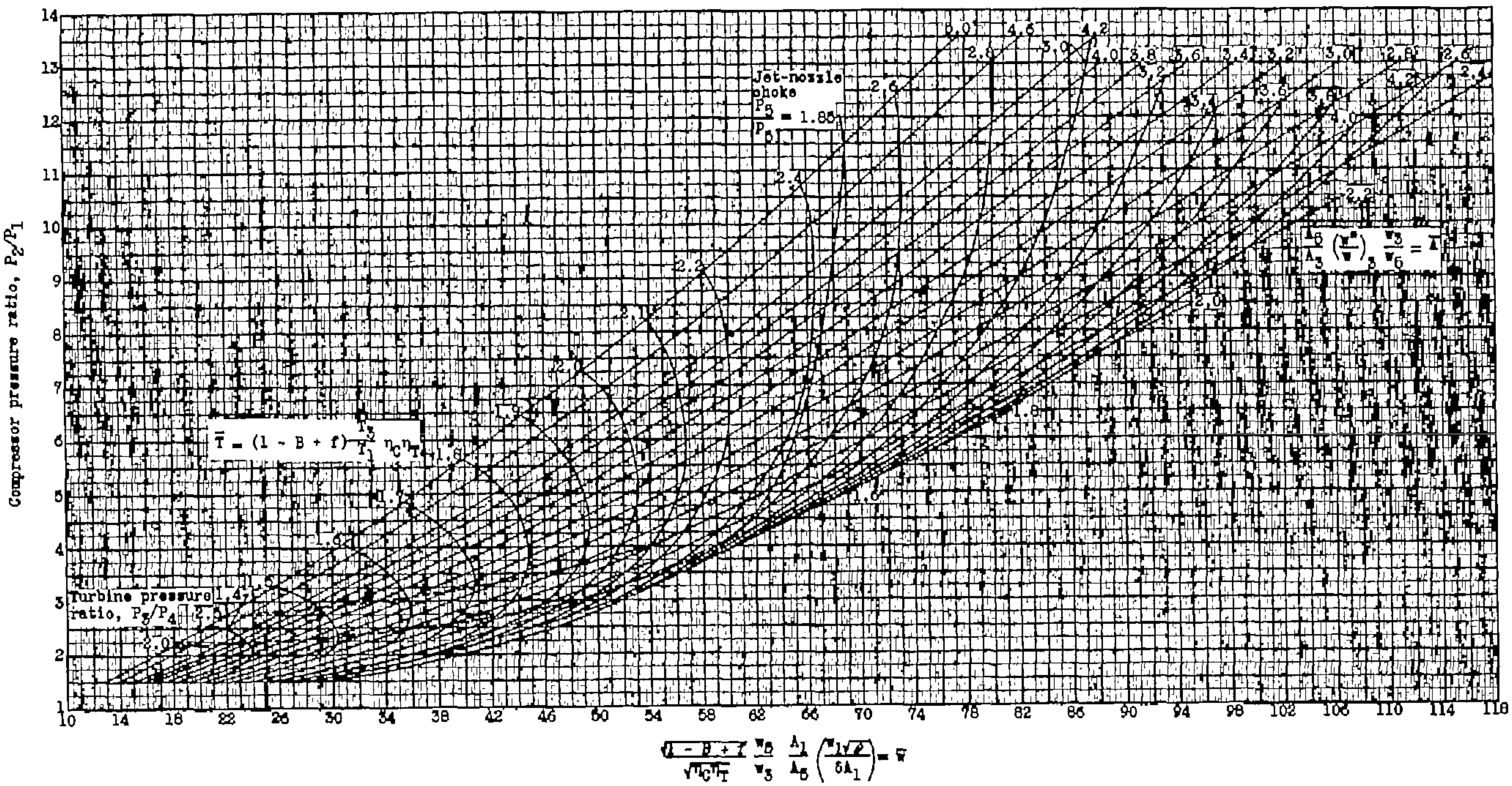

Figure 4. - Chart for estimating compressor equilibrium operating line. Ram pressure ratio, P_1/p_0, 1; combustor pressure ratio, P_3/P_2, 0.97.

(A large working copy of this chart may be obtained by using the request card bound in the back of the report.)

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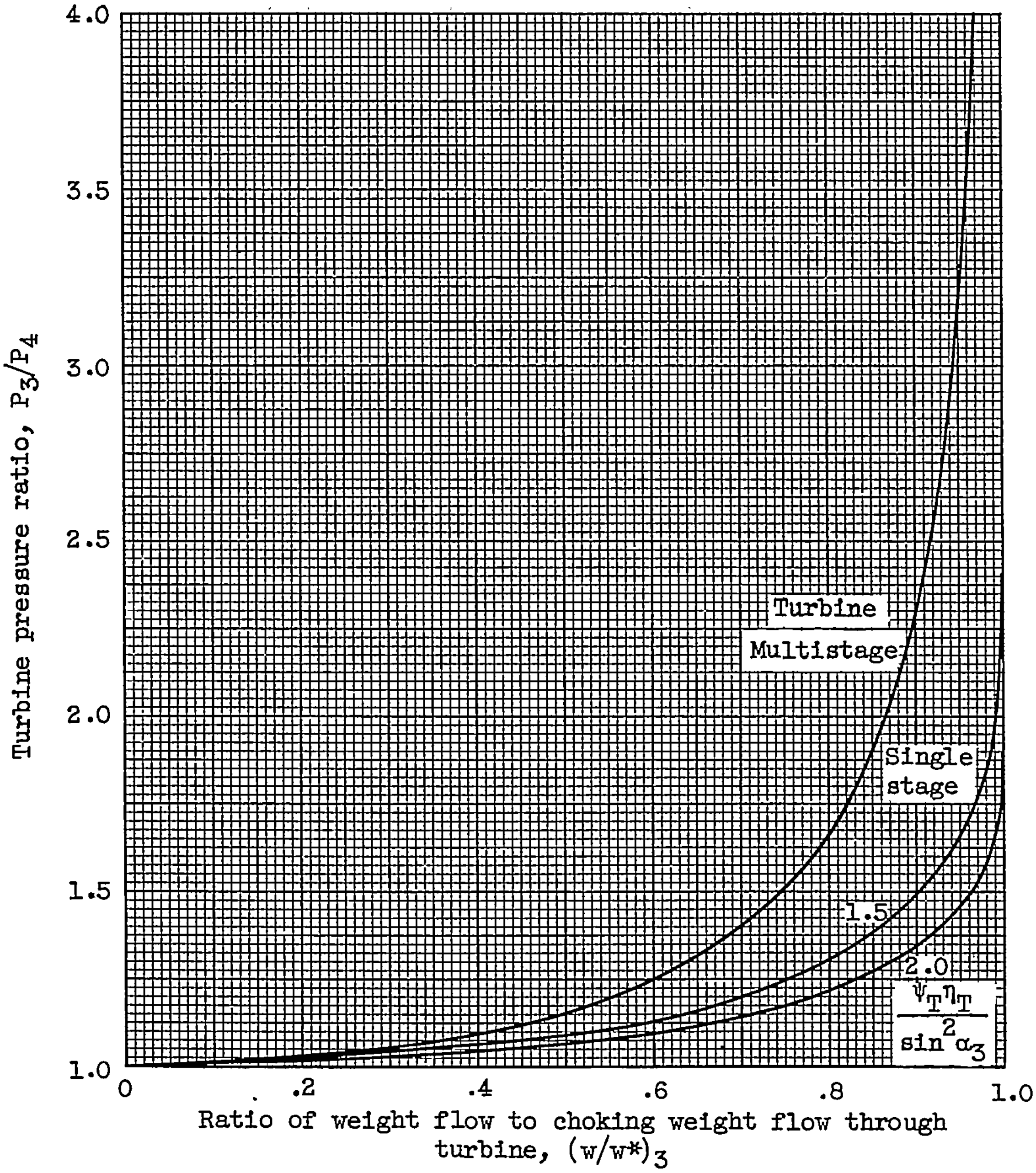

Figure 5. - Effect of turbine pressure ratio on weight flow.

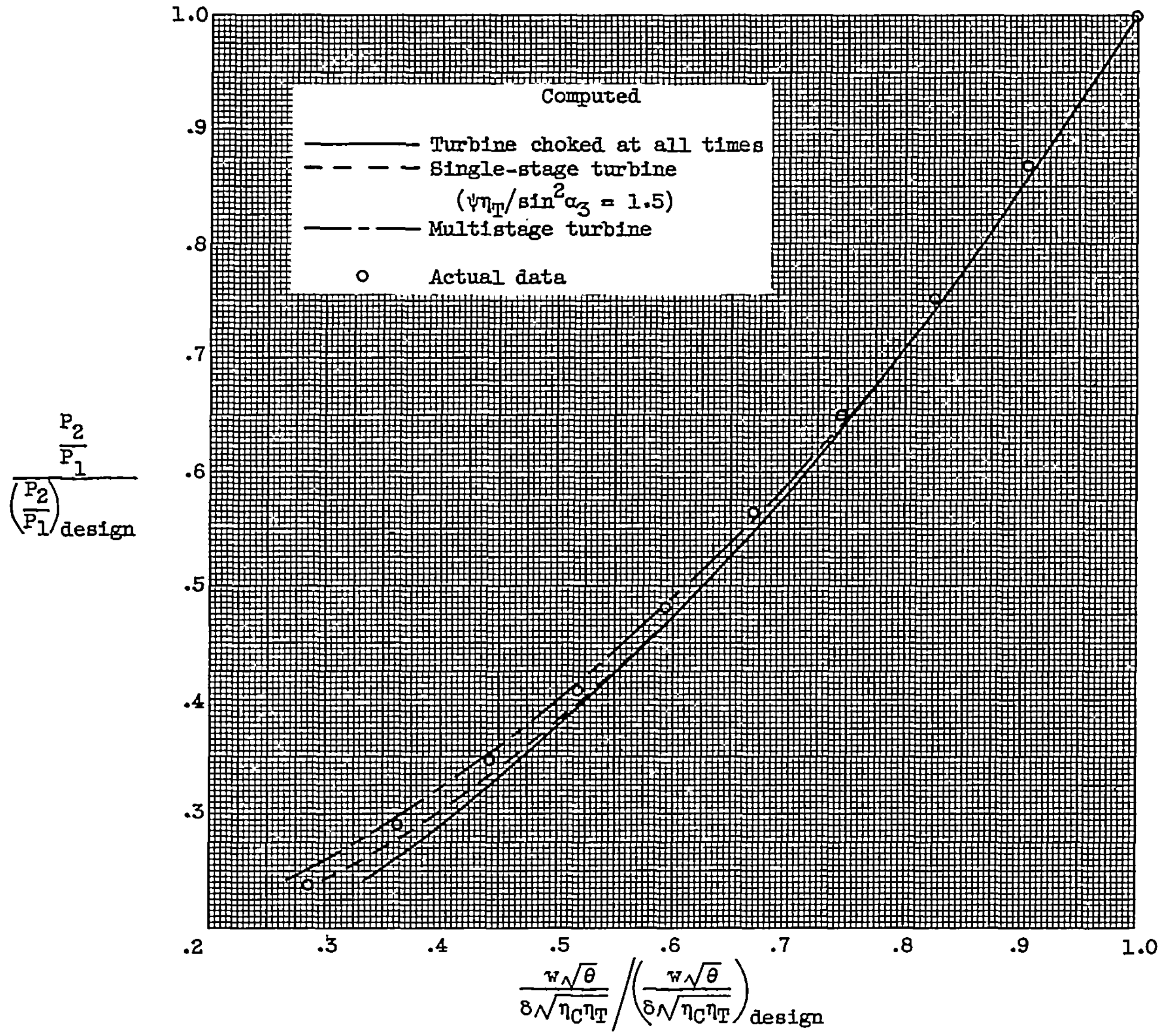

Figure 6. - Comparison of predicted equilibrium operating line with jet-engine test data. Design compressor pressure ratio, 6.6; $\left[(T_3/T_1)\eta_C\eta_T\right]_{design}$, 2.8; B = f.